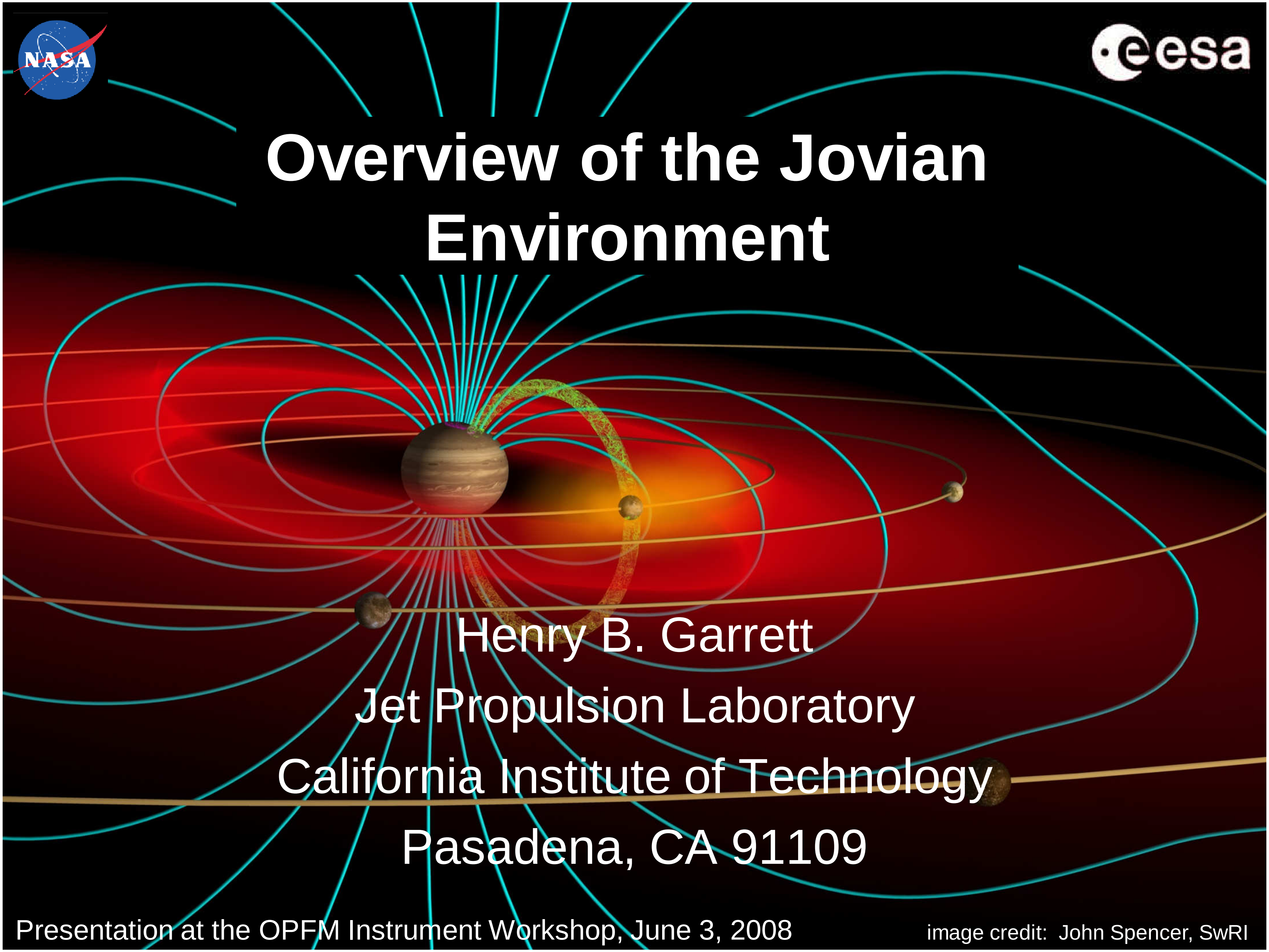

Overview of the Jovian Environment

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California Institute of Technology
Pasadena, CA 91109

Presentation at the OPFM Instrument Workshop, June 3, 2008

image credit: John Spencer, SwRI

AGENDA

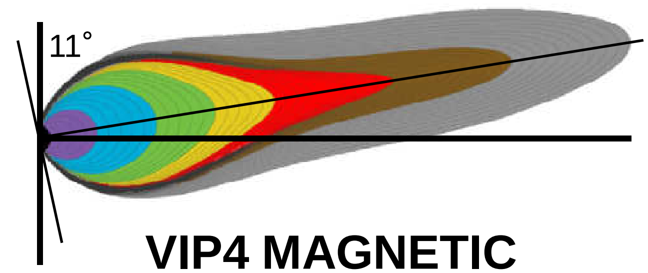
Outline:

- Status of current models of Jovian radiation environment
  - Jovian magnetosphere overview (magnetic field, plasma torus/disc, aurora)
  - Divine radiation model, GIRE (Galileo Interim Radiation Electron) model update, and Inner Belts update for electrons
  - Statistical variations of electron environment with R_j
  - HIC (Heavy Ion Counter) model of high energy O, S, and C ions
- Europa and Ganymede radiation environments
  - Overview of Europa's and Ganymede's interactions with Jupiter's magnetosphere
  - Radiation at surface of Europa and Ganymede
- Outstanding radiation environment issues

Jupiter's Magnetosphere

Characteristics	***Earth***	***Jupiter***
Equatorial radius (km)	6.38×10^3	7.14×10^4
Magnetic moment (G-cm^3)	8.1×10^{25}	1.59×10^{30}
Rotation period (hr)	24.0	10.0
Aphelion/perihelion (AU)	1.01/0.98	5.45/4.95

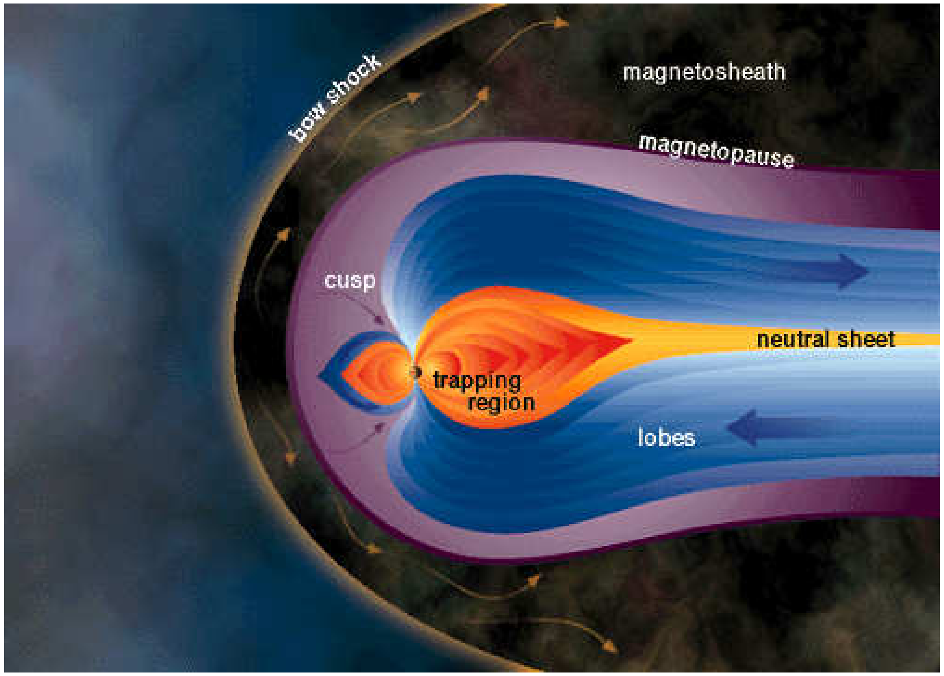
- Jupiter is roughly 10 times the size of the Earth while its magnetic moment is 2×10^4 larger.
- As the magnetic field at the equator is proportional to the magnetic moment divided by the cube of the radial distance, the Jovian magnetic field is proportionally 20 times larger than the Earth's.

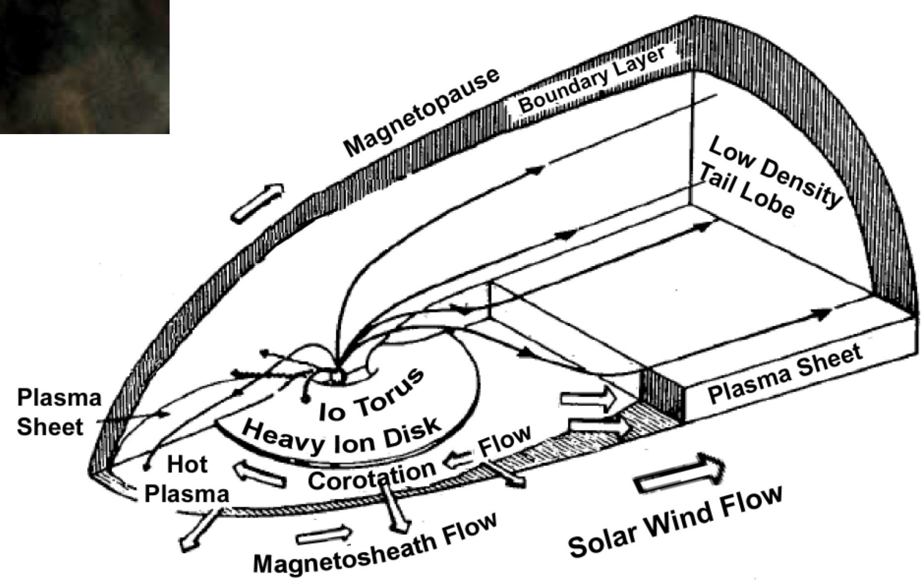


VIP4 MAGNETIC FIELD MODELS

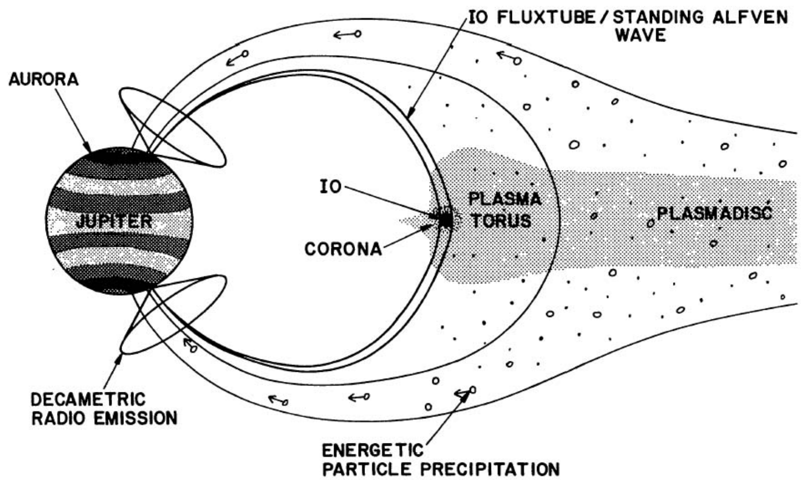
- The energy and flux levels of trapped particles in the Jovian system can be much higher than those at the Earth or in the interplanetary space.

The Jovian Magnetosphere

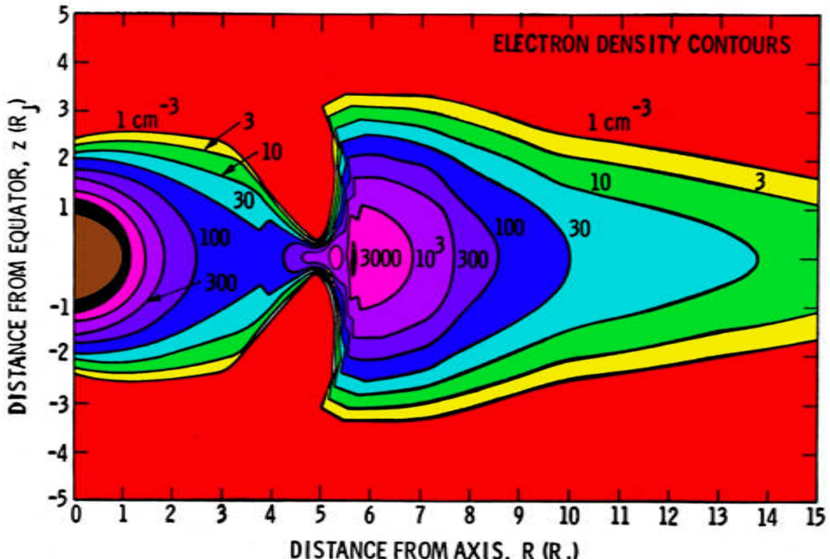




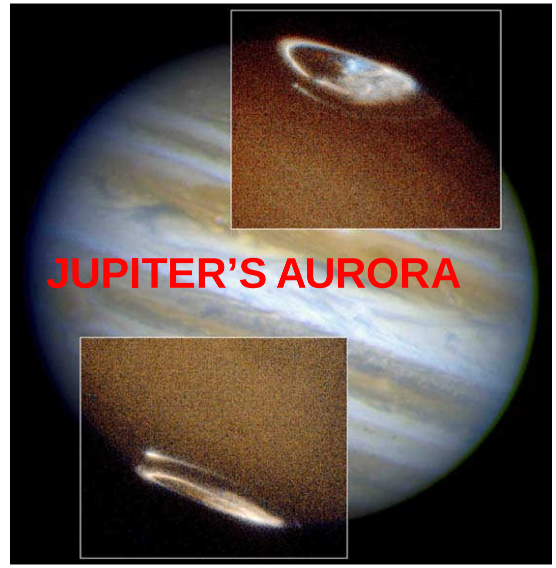
Jupiter's Plasma Environment and Aurora

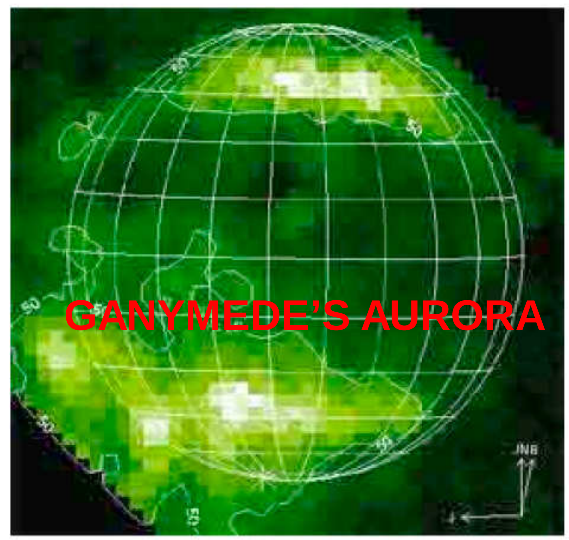


SCHEMATIC OF JUPITER'S INNER MAGNETOSPHERE



JUPITER'S LOW ENERGY PLASMA ENVIRONMENT





Modeling The Jovian Radiation Environment

The Jovian Radiation Environment

Current Radiation Models:

- Divine Electron and Proton Models

  Divine, N. T., Garrett, H. B., "Charged Particle Distributions in Jupiter's Magnetosphere", J. Geophys. Res., 88, 6889-6903, 1983

- Galileo Interim Radiation Electron Model

  Garrett, H. B., I. Jun, J. M. Ratliff, R. W. Evans, G. A. Clough, and R.W. McEntire, "Galileo Interim Radiation Electron Model", JPL Publication 03-006, 72 pages, The Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 2003.
  http://www.openchannelfoundation.org/projects/GIRE/

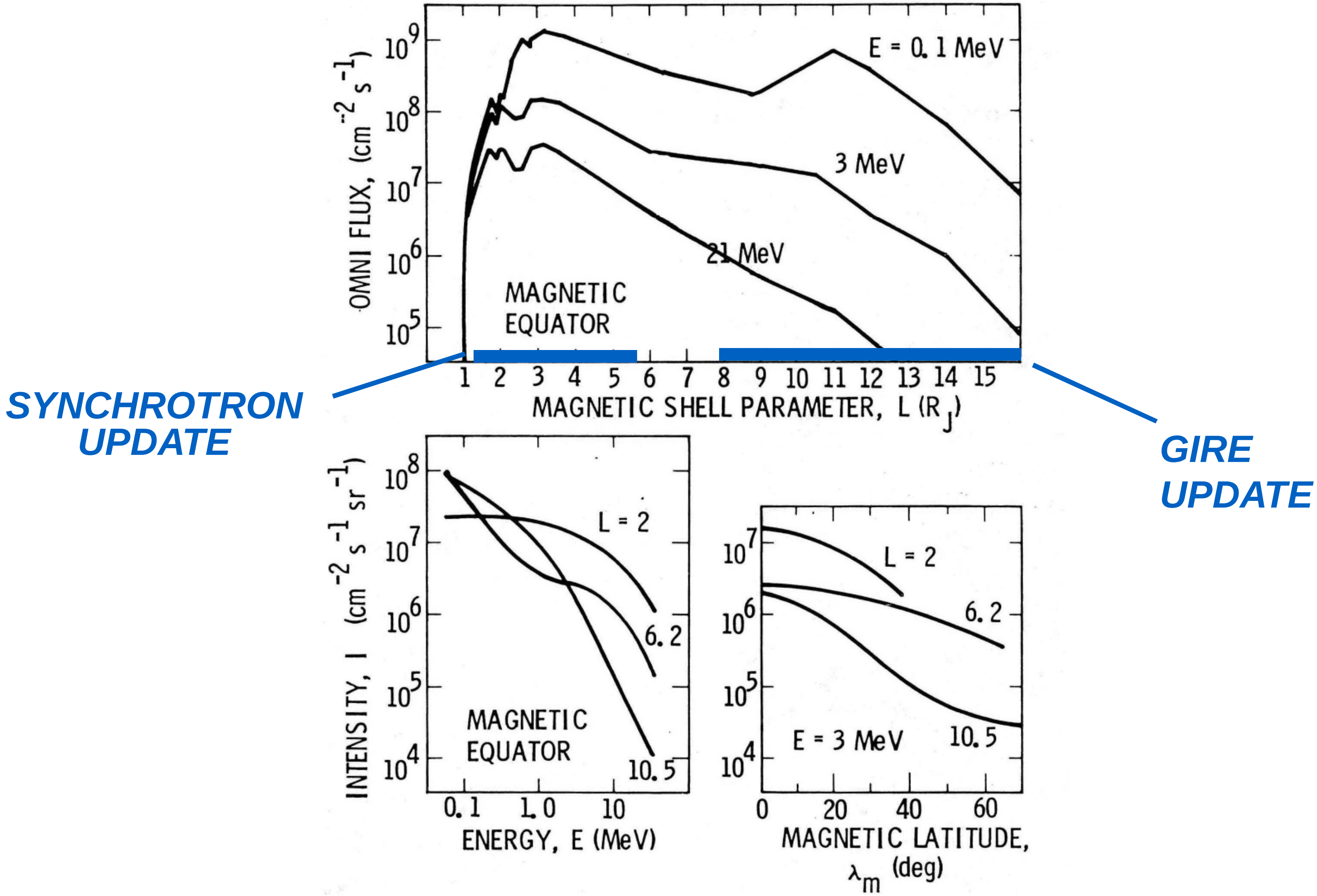
- Salammbô

  Sicard, A., and S. Bourdarie, "Physical Electron Belt Model from Jupiter's surface to the orbit of Europa" J. Geophys. Res., 109, A02216, doi:10.1029/2003JA010203, 2004.

Divine "Family" of Radiation Models

- Jupiter radiation modeling based on original "Divine" model--de-facto standard Jupiter radiation environment model since 1983.
  - Pioneer and Voyager in-situ data plus Earth-based Synchrotron observations
  - Limited in temporal and spatial coverage
- Galileo orbited Jupiter starting in 1995
  - Total 35 orbits
  - Extensive scientific data return
- New Jupiter radiation environment models derived from:
  - Energetic Particle Detector (EPD) for high energy trapped electrons
  - Heavy Ion Counter (HIC) for heavy ions

ORIGINAL DIVINE HIGH ENERGY ELECTRON MODEL



Galileo Interim Radiation Electron Model

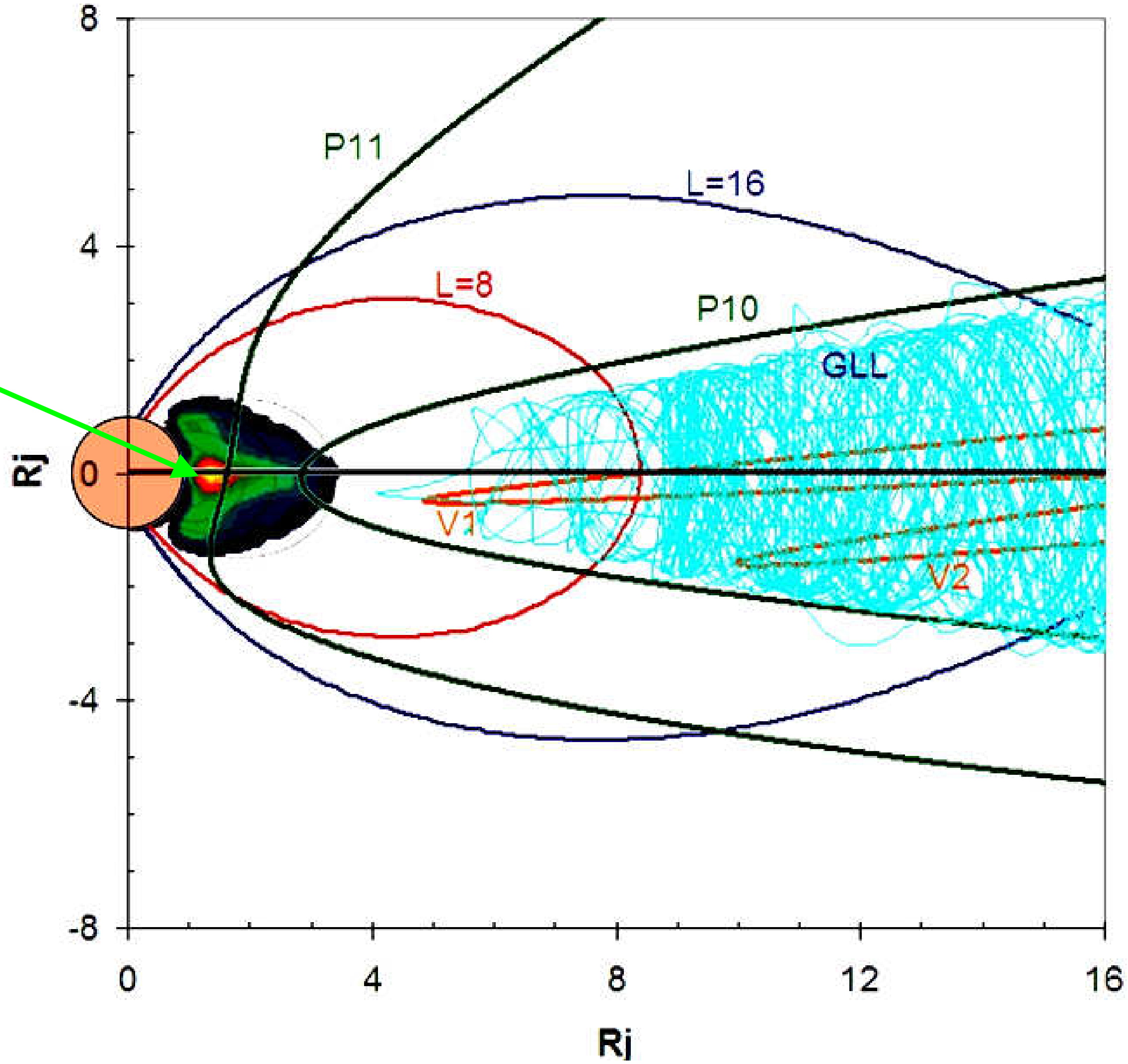
*GIRE Model**

- GIRE is a significant improvement over the Divine electron model.
- Uses in-situ data from 35 Galileo orbits--based primarily on EPD data
- Updated to fit synchrotron data within 5 Rj.
- Covers radial distance 1-4 and 8-16 Rj.
- Defines the trapped electron environment.
- Assumes Divine pitch angle distributions.
- Covers energy range 0.1 MeV to ~30 MeV.
- Assumes Divine proton model.

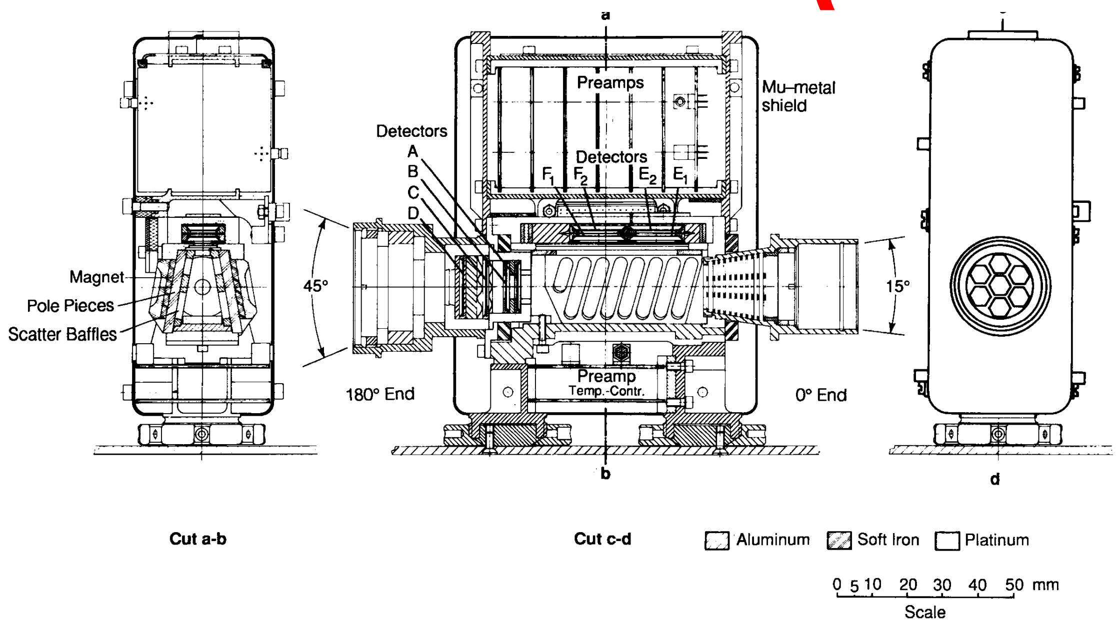
*Garrett et al., JPL Pub. 03-006 (2003)

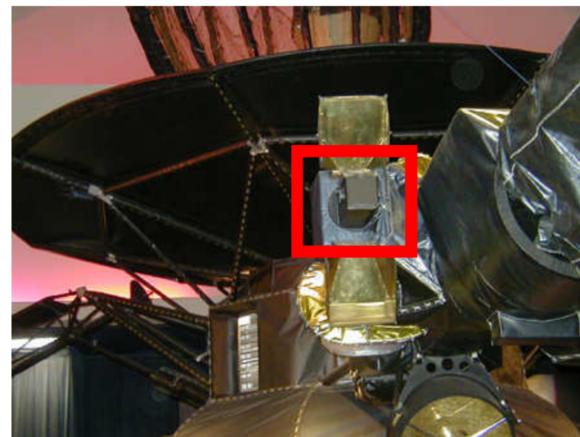
Pioneer 10-11, Voyager 1-2, and Galileo Trajectories

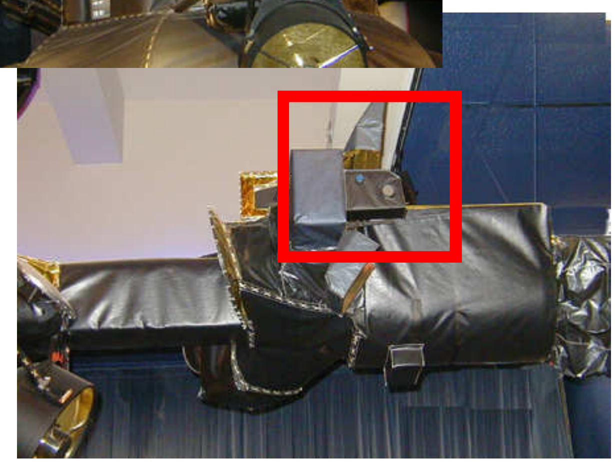
Synchrotron Data Range



EPD (LEMMS)





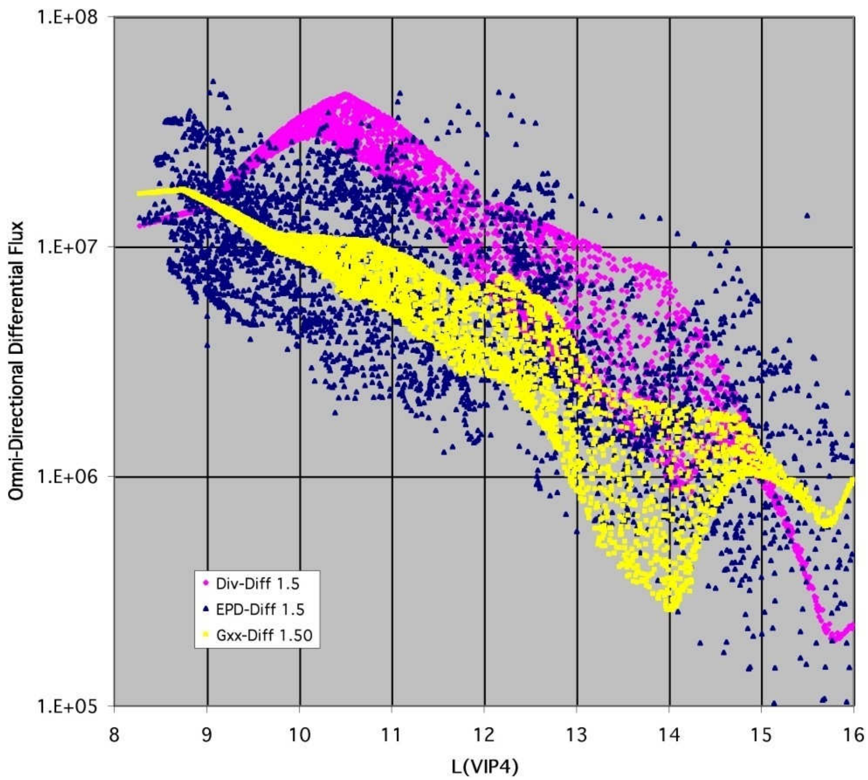


EPD=CMS+LEMMS

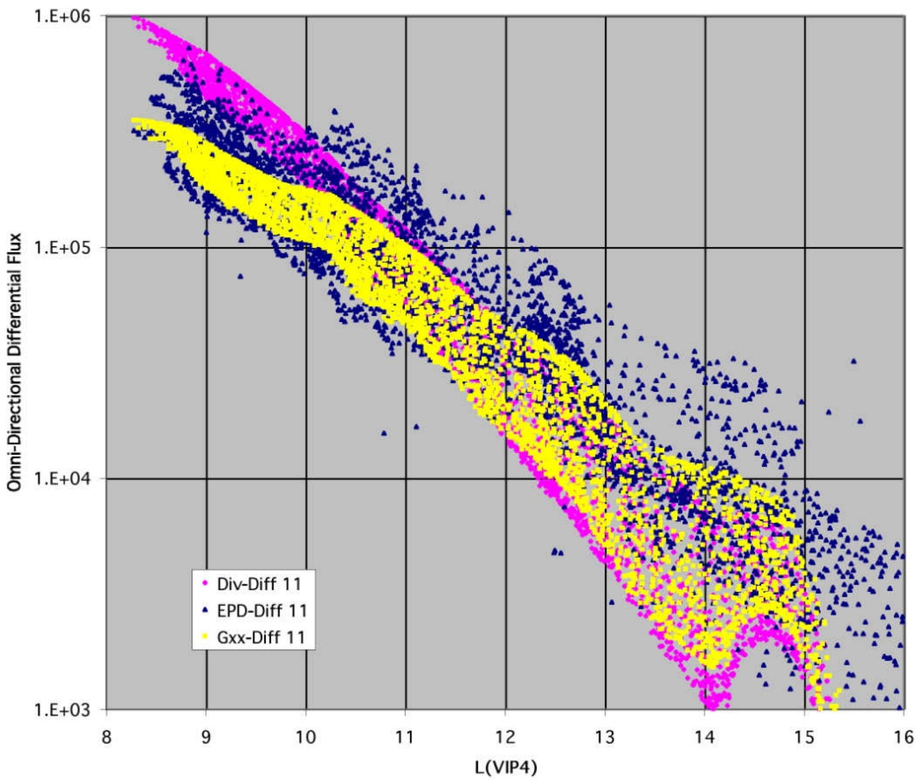
Channel Name	Nominal Energy Range (MeV)
F1	0.174-0.304
F2	0.304-0.527
F3	0.527-0.83
B1	1.5 – 10.5
DC2	^{3} 2.0
DC3	^{3}11.0

Divine Model, GIRE Model, EPD Data

Comparisons between observed EPD (blue) fluxes and Divine (pink) and GIRE (yellow) predictions



1.5 MeV ELECTRONS

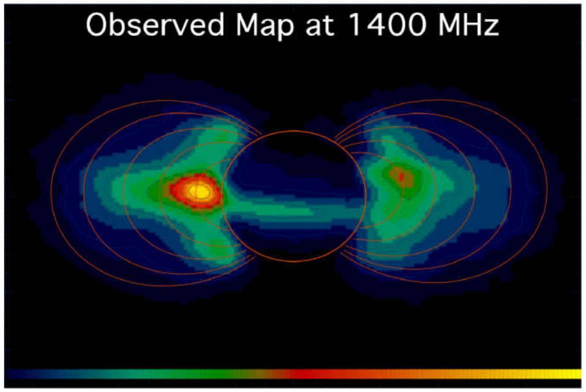


11 MeV ELECTRONS

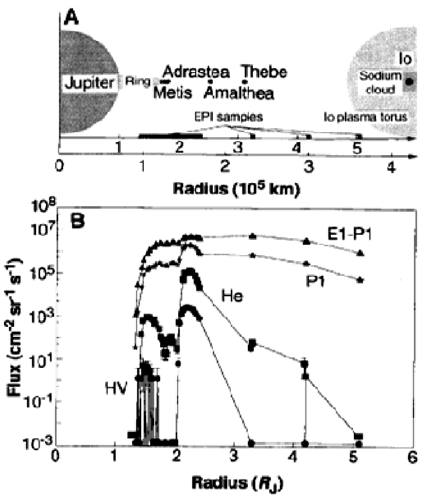
Pink = Divine; Yellow = GIRE; Blue = EPD data

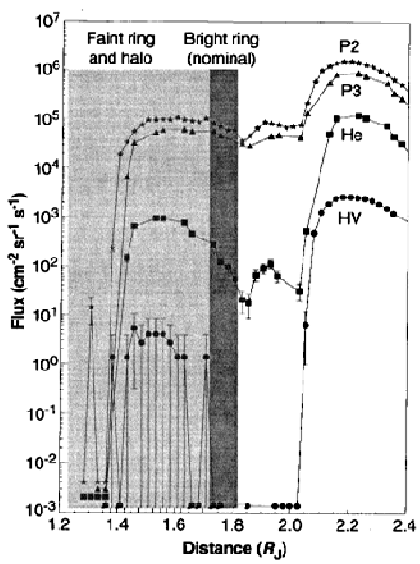
Update of Inner Radiation Belt Model

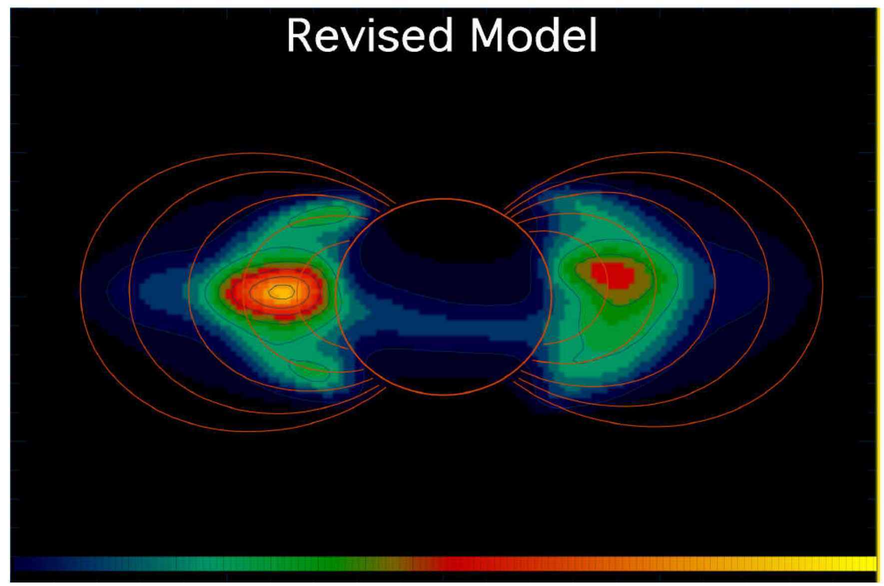
Synchrotron predictions based on update to Divine Model



Synchrotron Observations

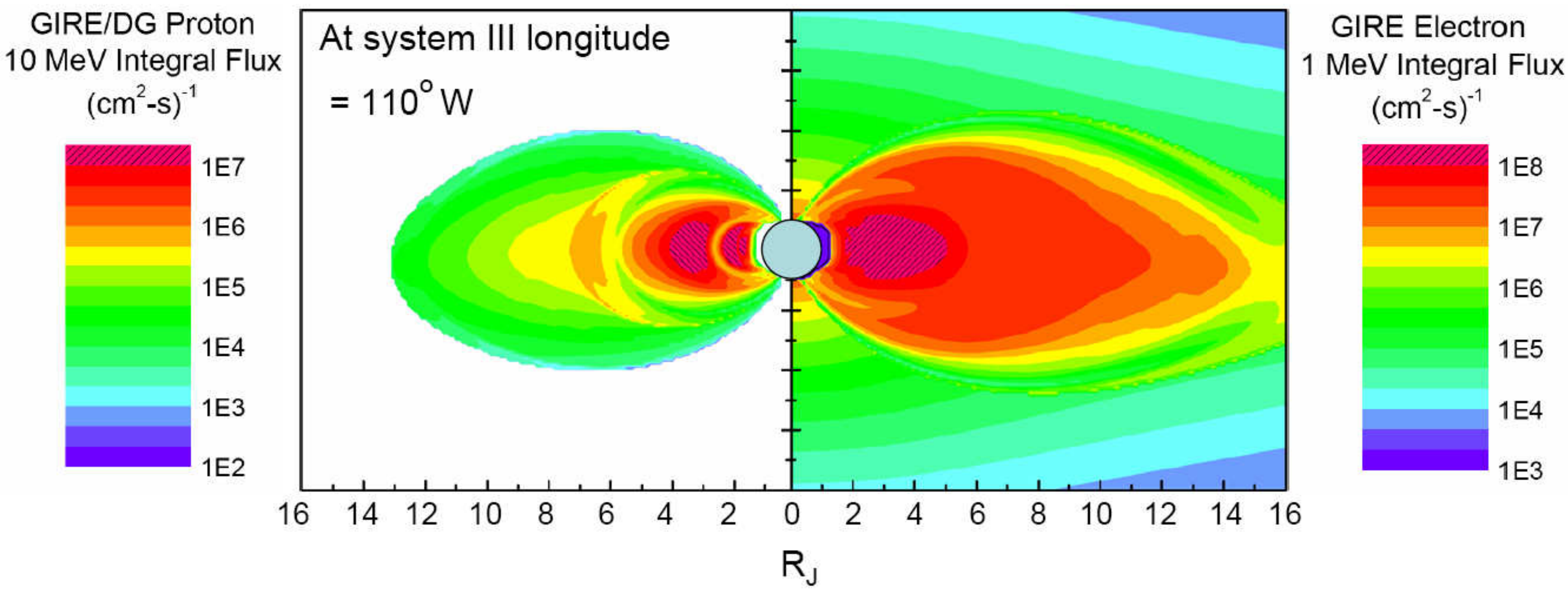






Galileo Probe Observations

DIVINE + GIRE JOVIAN RADIATION MODELS



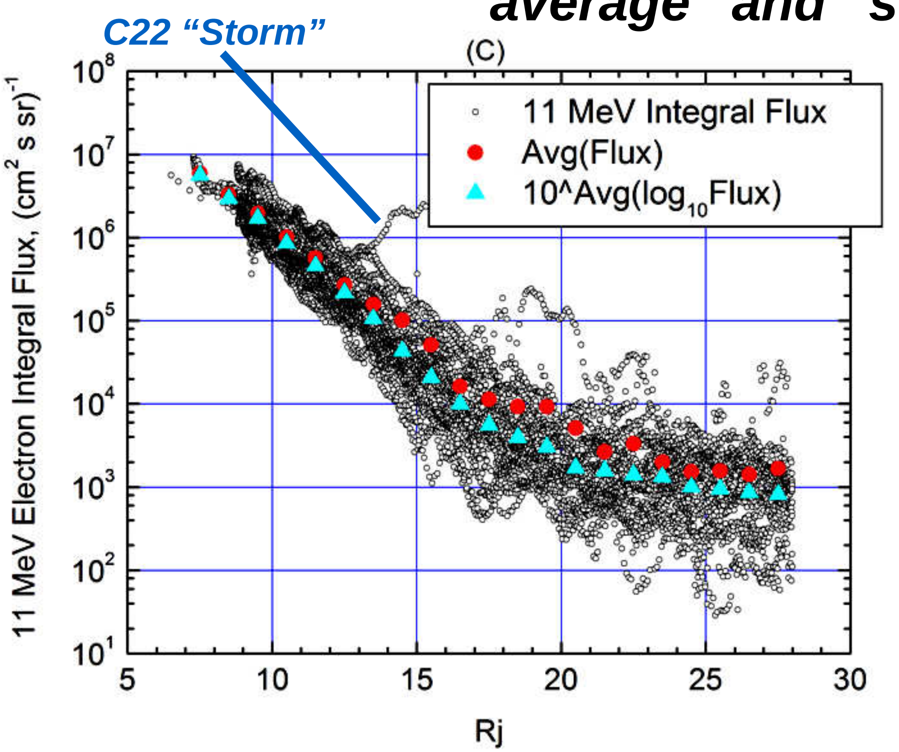
Contour plots of ≥1 MeV electron and ≥10 MeV proton integral fluxes at Jupiter. Coordinate system used is jovi-centric. Models are based on Divine/GIRE models. Meridian is for System III 110° W.

Statistics of High-Energy Electron Populations based on the EPD Measurements*

*Jun et al., Icarus (2005).

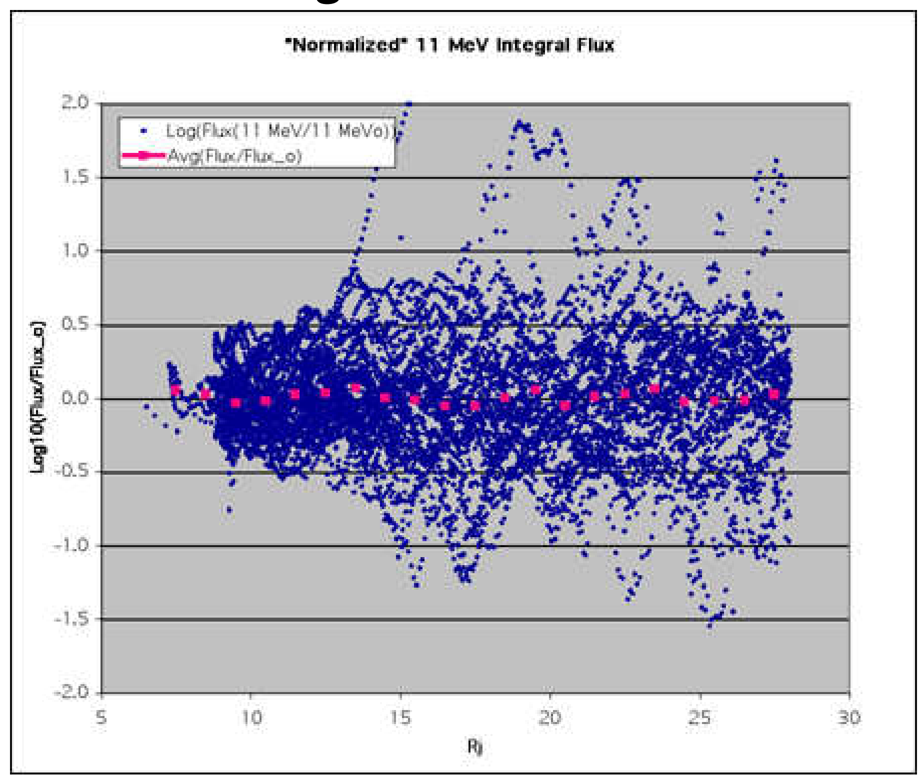
Trapped Electron Radial Variations

Variations in EPD Fluxes with distance from Jupiter showing "average" and "storm" variations



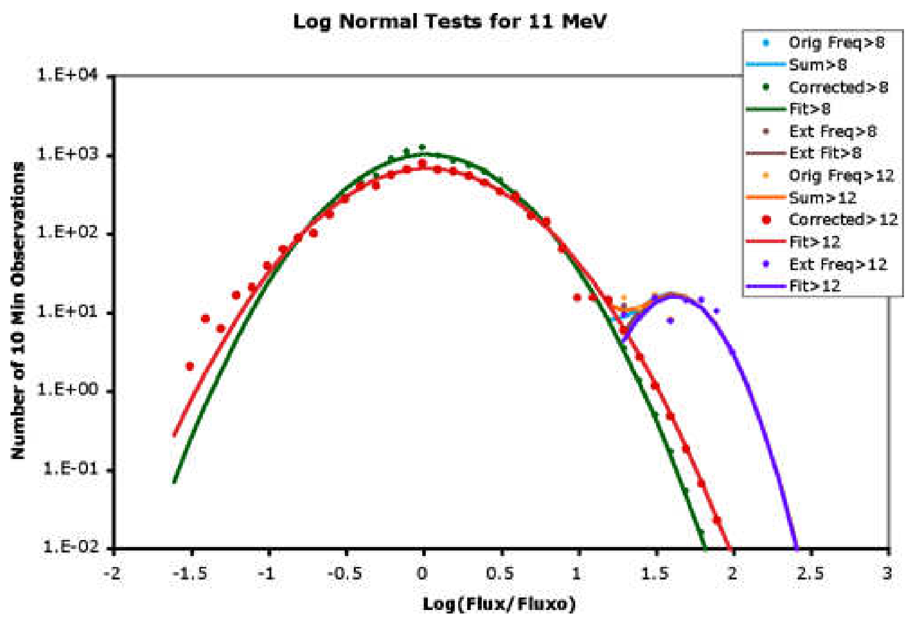
Galileo EPD 11 MeV particle fluxes vs radial distance

Logarithms Of Ratio Of EPD To Average Flux Vs L-shell



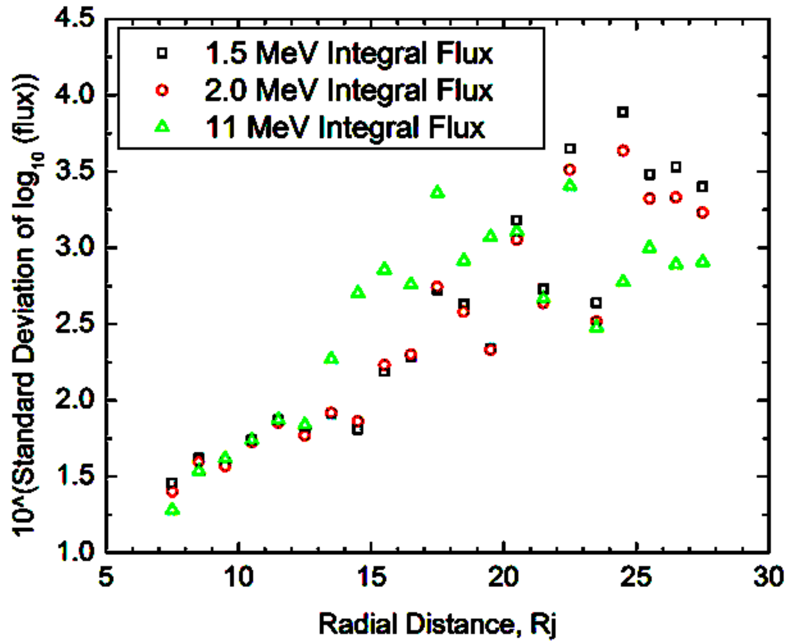
Statistical Variations of Jovian Particle Fluxes

Examples of log-normal fits to the Galileo electron fluxes



Log-Normal fits to 11 MeV Electrons

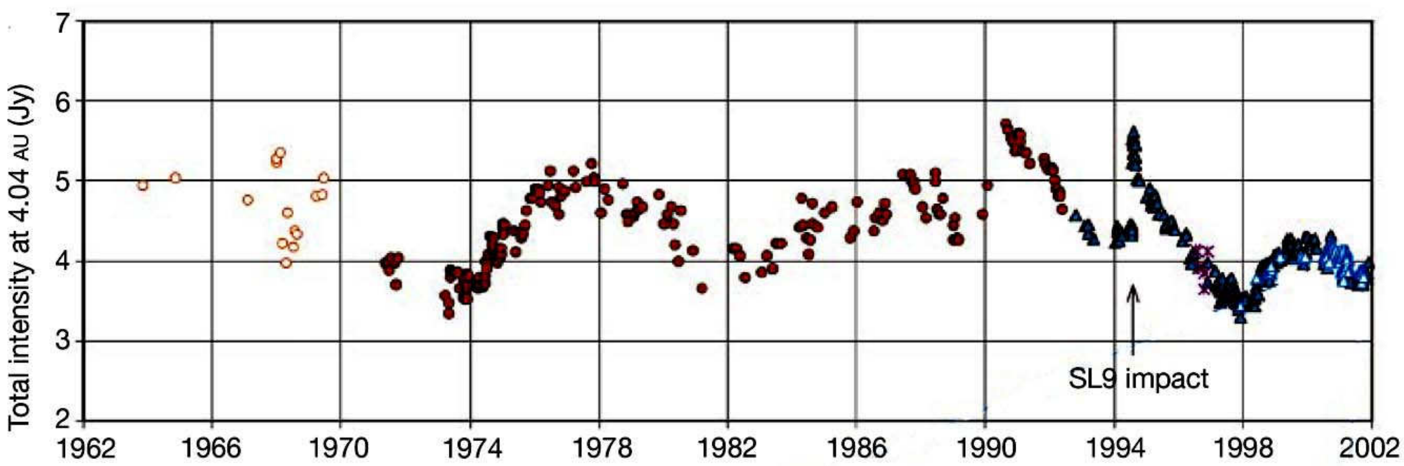
Standard Deviations of Electron Fluxes versus Rj



Jovian Radiation "Climatology"

QUESTION: How does the jovian environment change on the time scale of years to decades?

- –The "climate", based on the Pioneer (Dec 1973, Dec 1974) and Voyager encounters (Mar 1979, July 1979) versus Galileo (1995-2003), implies variations of ***2-3*** (Divine vs GIRE).
- –The Earth-based Goldstone Apple Valley Radio Telescope (GAVRT) study of the jovian synchrotron radiation shows variations of ***~2*** in the trapped, relativistic electron populations over 4 decades in inner electron belt (~1.5-2 L).

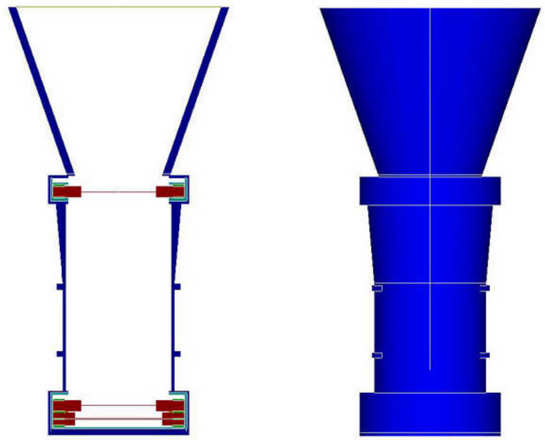


Caltech Galileo Heavy Ion Counter Radiation Model

HIC Model

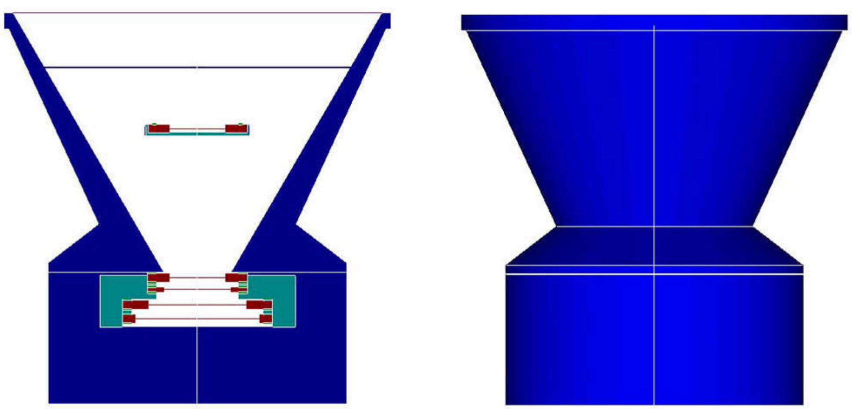
- Used data from 31 of the 35 Galileo orbits.
- Covers radial distance from 2.5 Rj to 30Rj.
- Models three ions: Oxygen, Carbon, and Sulfur.
- Covers energy range ~6-200 MeV/nucleon.
- Average model
  – Model is useful for defining heavy ion spectra for SEE evaluations.

HIC (Heavy Ion Counter)

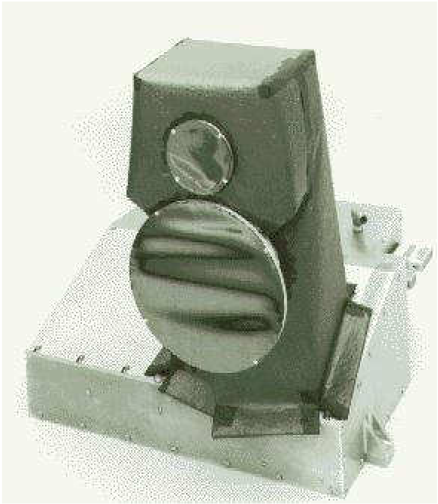


LET B

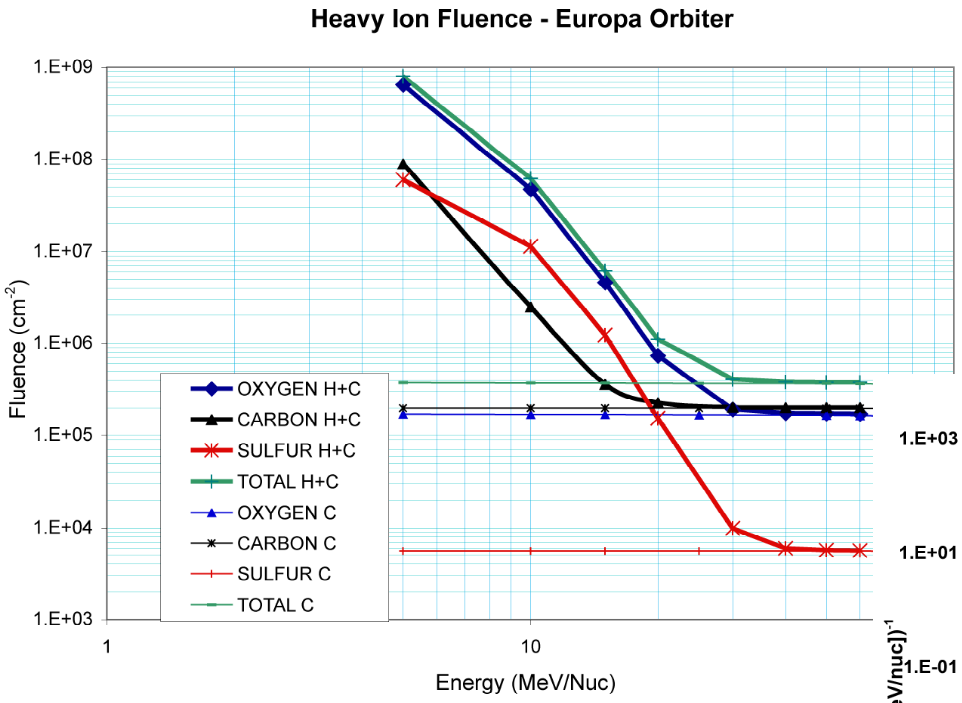
- HIC composed of two solid-state Low Energy Telescopes (LETs): LET B and LET E.
- LETs are standard dE/dx vs residual energy instruments using solid state detectors to make measurements over broad energy range.
- Particle species discriminated by using energies deposited in each detector.



LET E

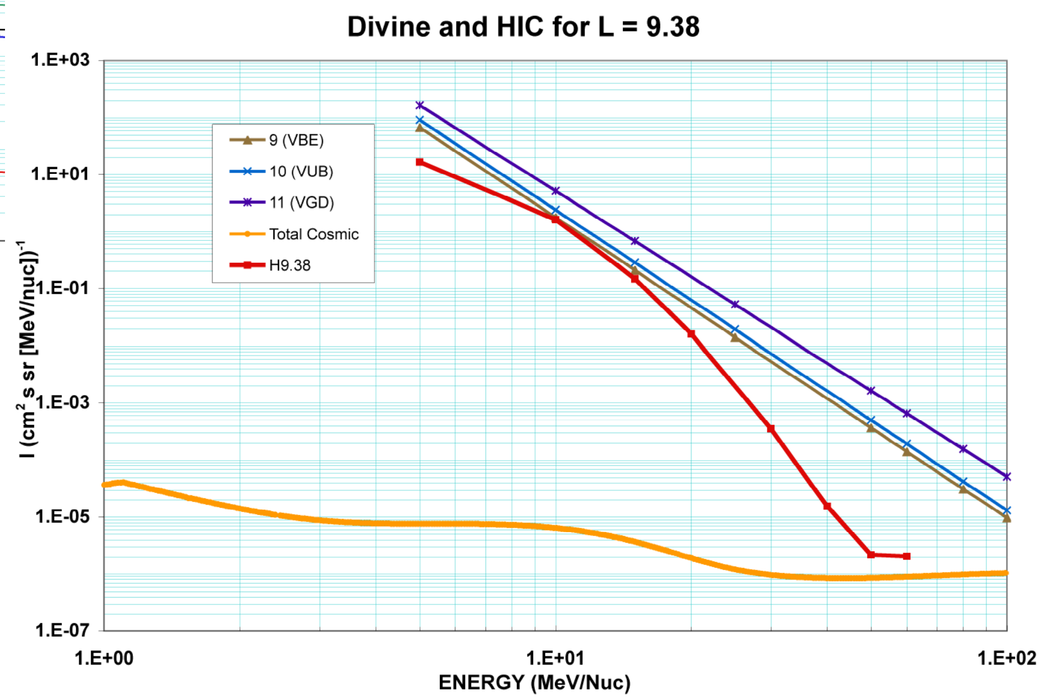


HIC Predictions

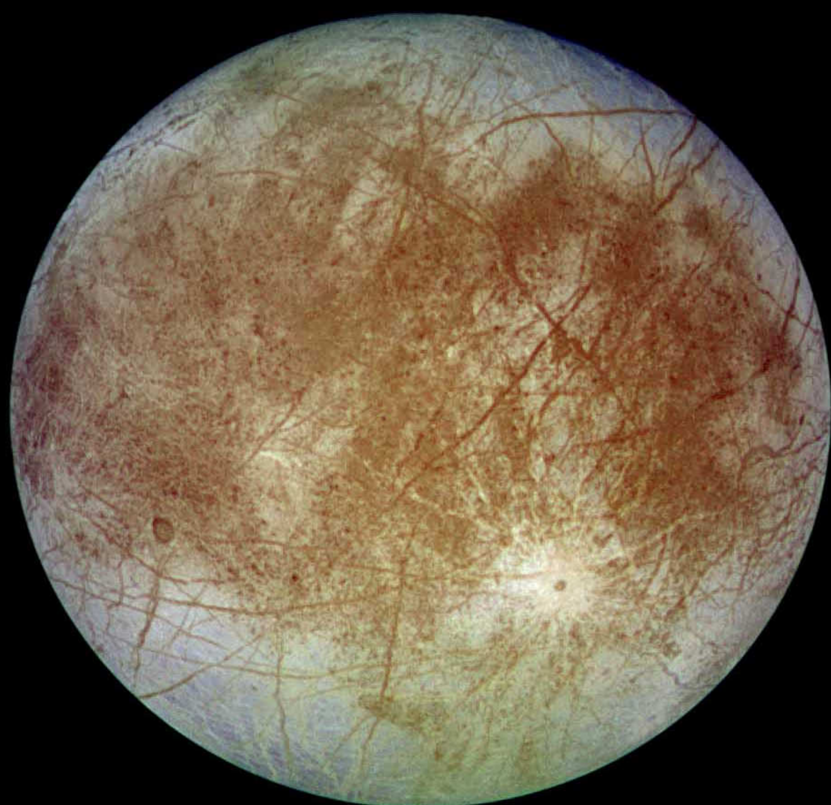


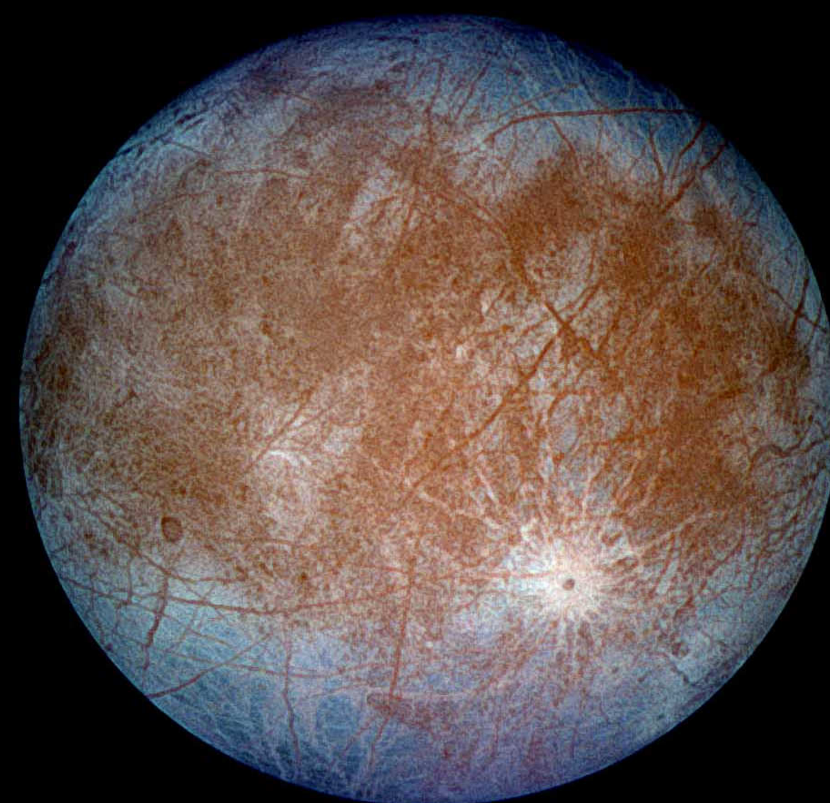
Modeled Fluxes at 9.38 Rj

Europa Orbiter Mission Fluences “EO9935”

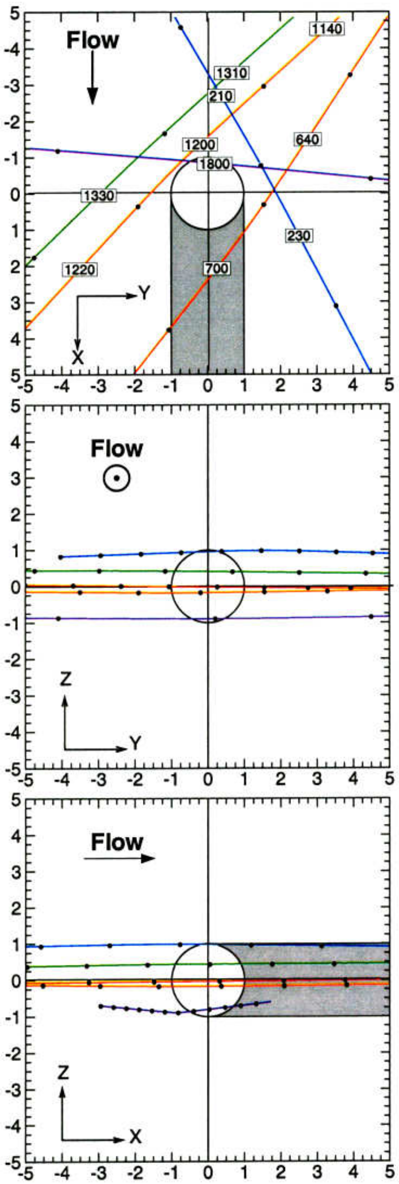


Europa

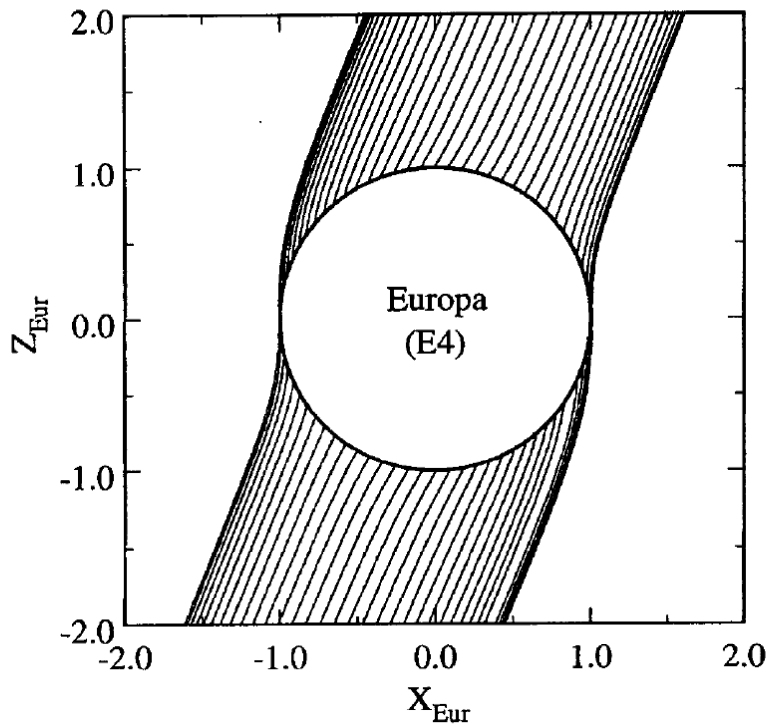




Europa's Magnetic Field Environment

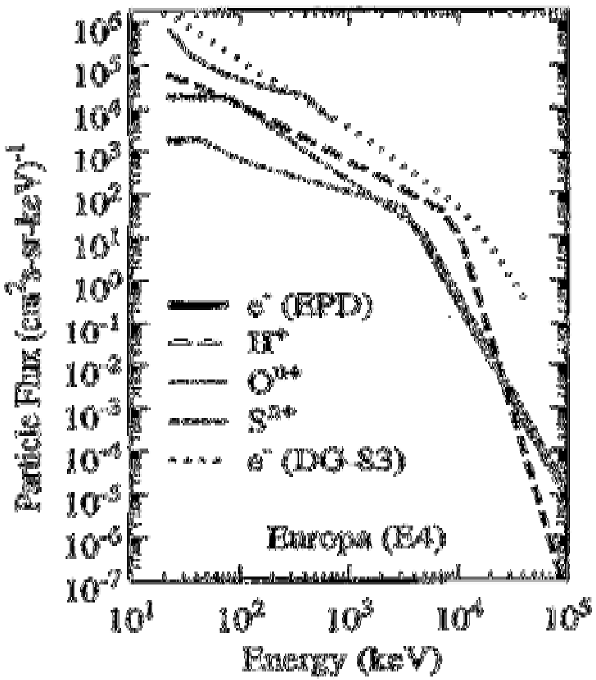


Europa flybys E4 (red), E12 (orange), E14 (green), E19 (blue), and E26 (purple) by Europa. Cartesian Coordinates: X along flow direction, Y along Europa-Jupiter vector, Z along spin axis.



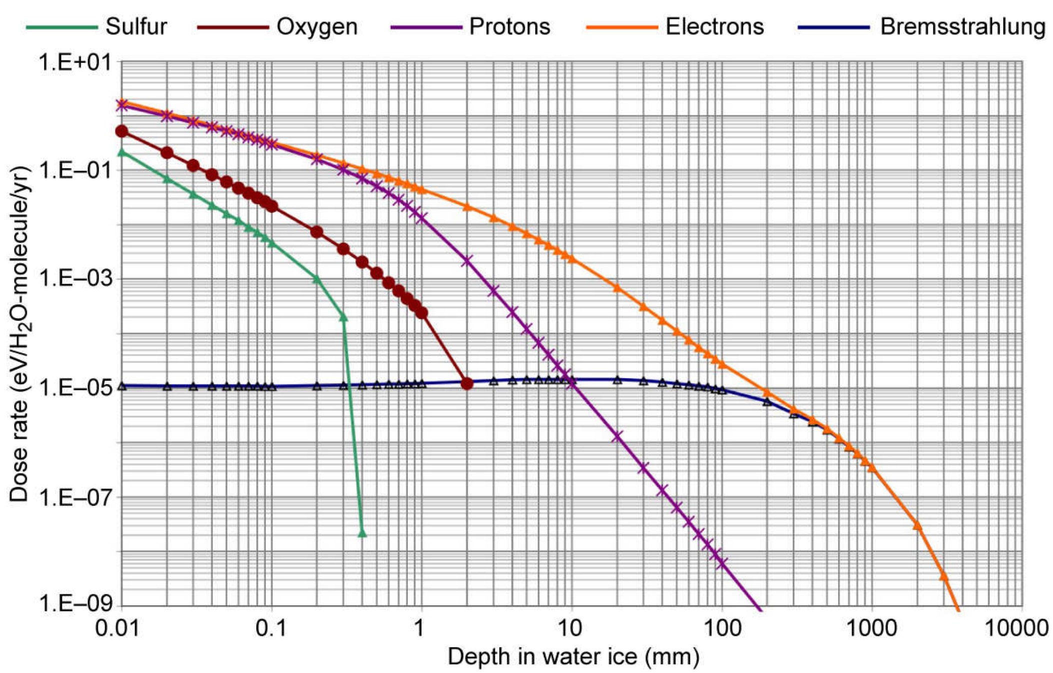
E4 magnetic field line configuration in X_s-Z_s plane from vacuum superposition of external jovian magnetic field (Khurana, 1997) for System III location.

Radiation Environment at Europa's Surface

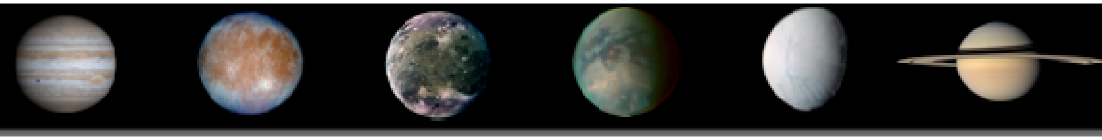


Flux spectra from EPD measurements at Europa during E4 encounter (Cooper et al., 2001). Electron spectra from EPD at 20-700 keV and from Divine and Garrett (1983).

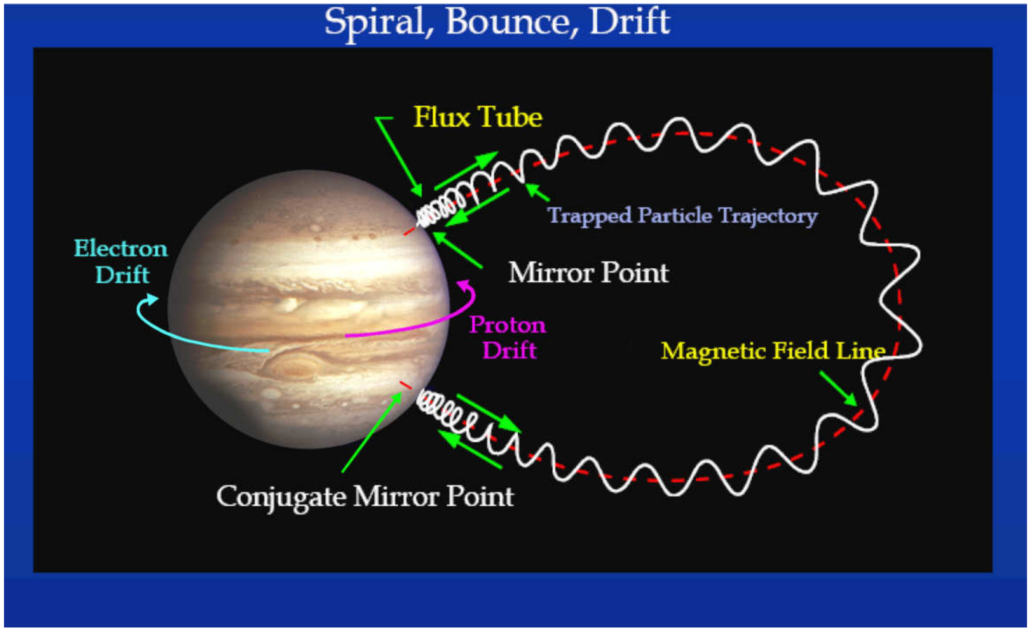
Dose rate (rad(H_2O)/s) vs depth curves for, electrons, protons, oxygen, and sulfur at apex of Europa's trailing hemisphere.



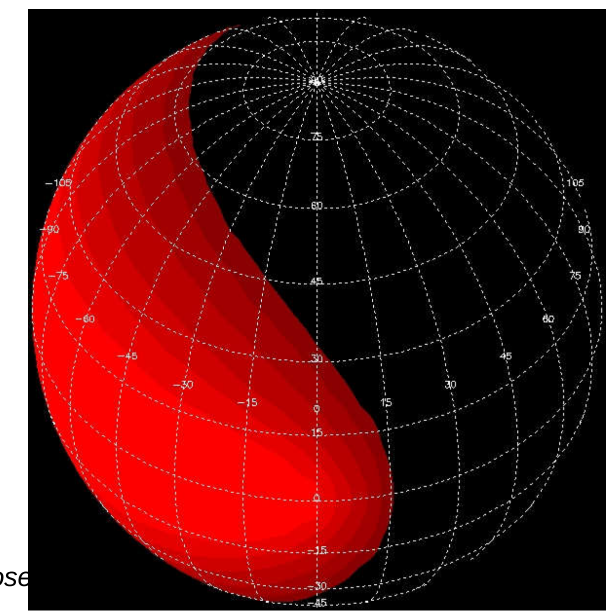
Paranicas et al. (2002)



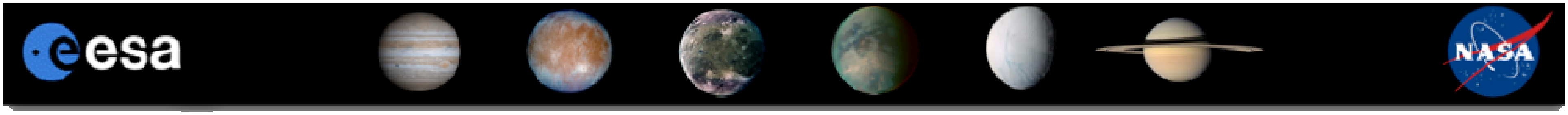
Trapped Particle Motion at Jupiter



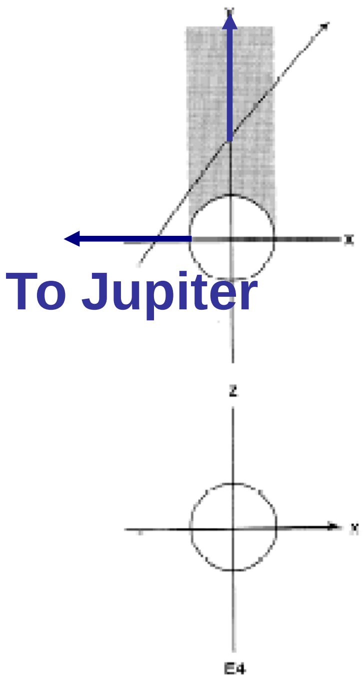
- If the magnetosphere of Jupiter is rigidly co-rotating, plasma flow speed at Europa's orbit (9.5 Rj) is about 118 km/s.
- Europa travels about 14 km/s in its orbit, so that charged particles are overtaking the satellite at all times.

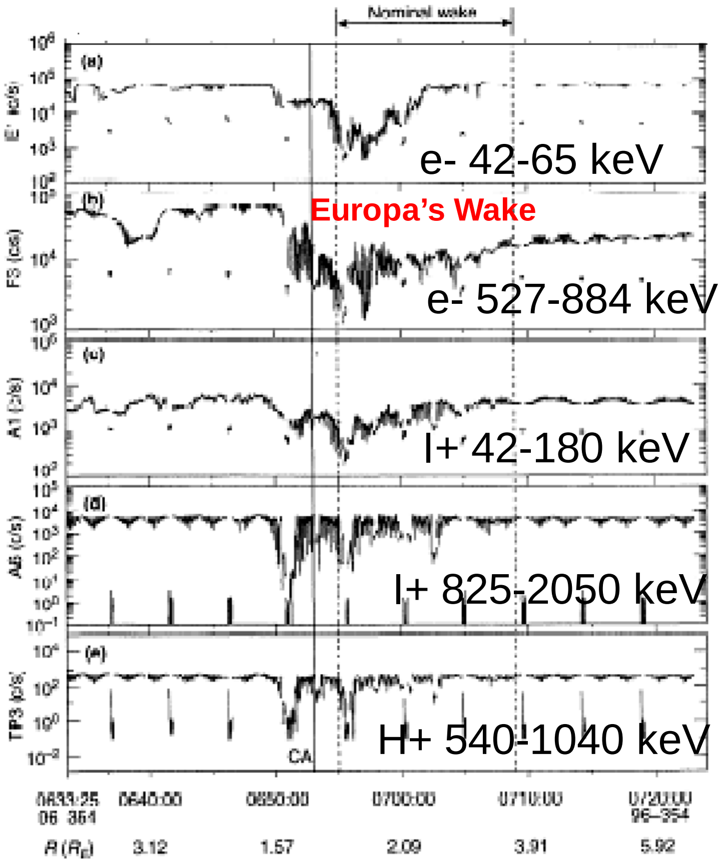


Particles impacting the trailing hemisphere leave regions above poles and leading hemisphere depleted of MeV electron flux (creating wake).



Measurements of Flux Reductions at Europa





EPD observed flux reductions in wake for orbit E4

EPD B1 (1.5-10.5 MeV) Electron Channel

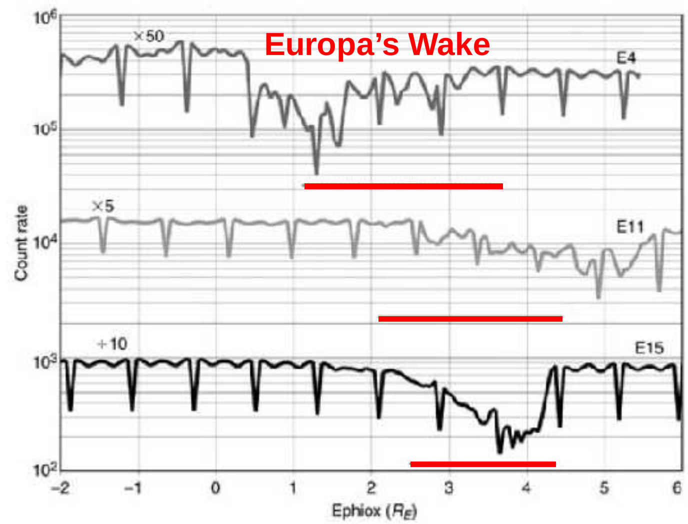
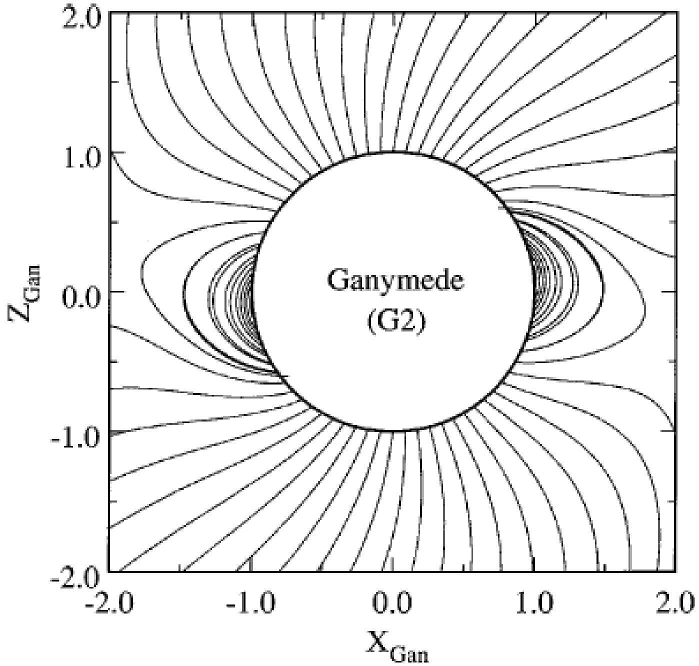


Figure 3. Spin-averaged count rates from the ~1.5–10.5 MeV electron channel on EPD plotted as a function of ephiox, the x-axis of the ephio system. The horizontal lines correspond to the nominal geometric wakes in ephio coordinates.

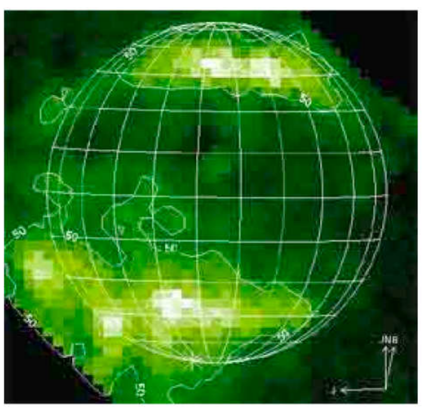
Paranicas et al., 2007)

GANYMEDE



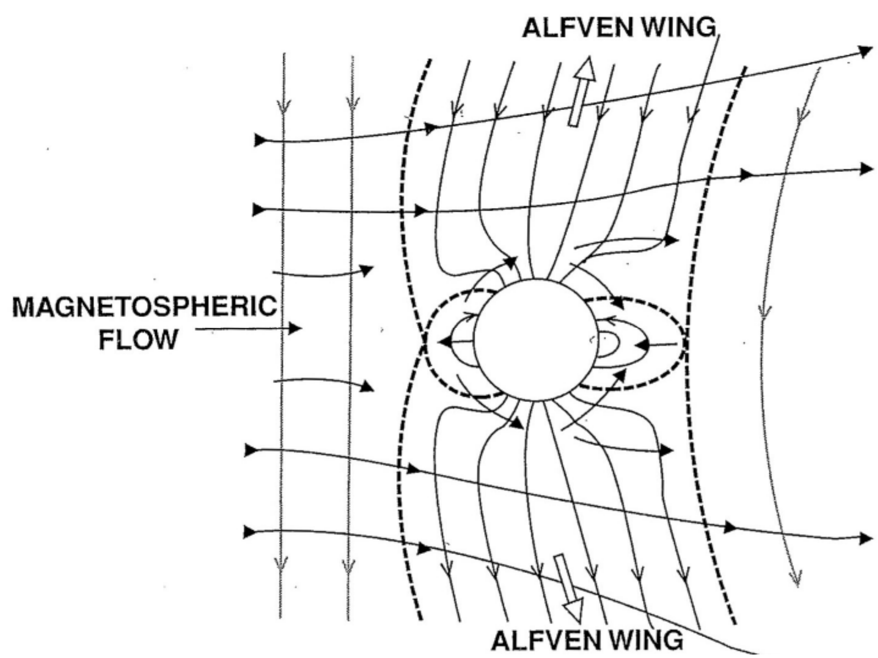
Ganymede's Magnetosphere

Magnetic field configuration at Ganymede (Cooper et al., Icarus, 2001)



Aurora at Ganymede.

Magnetospheric regions at Ganymede.

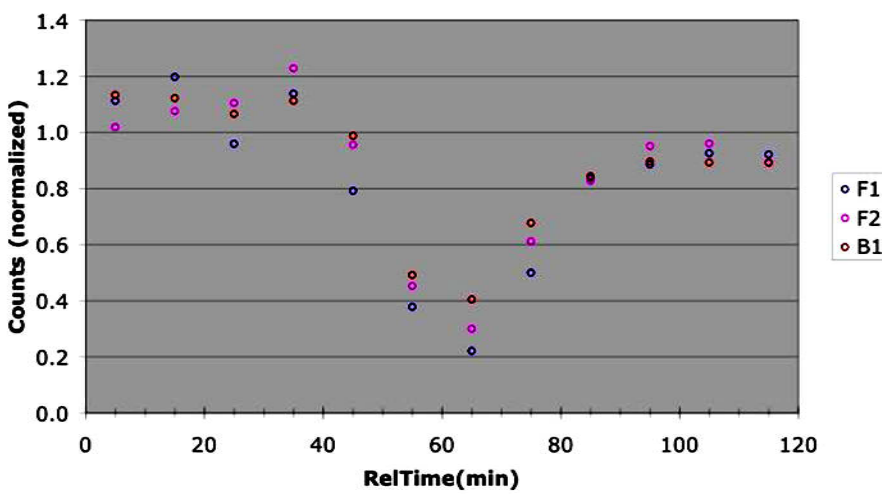


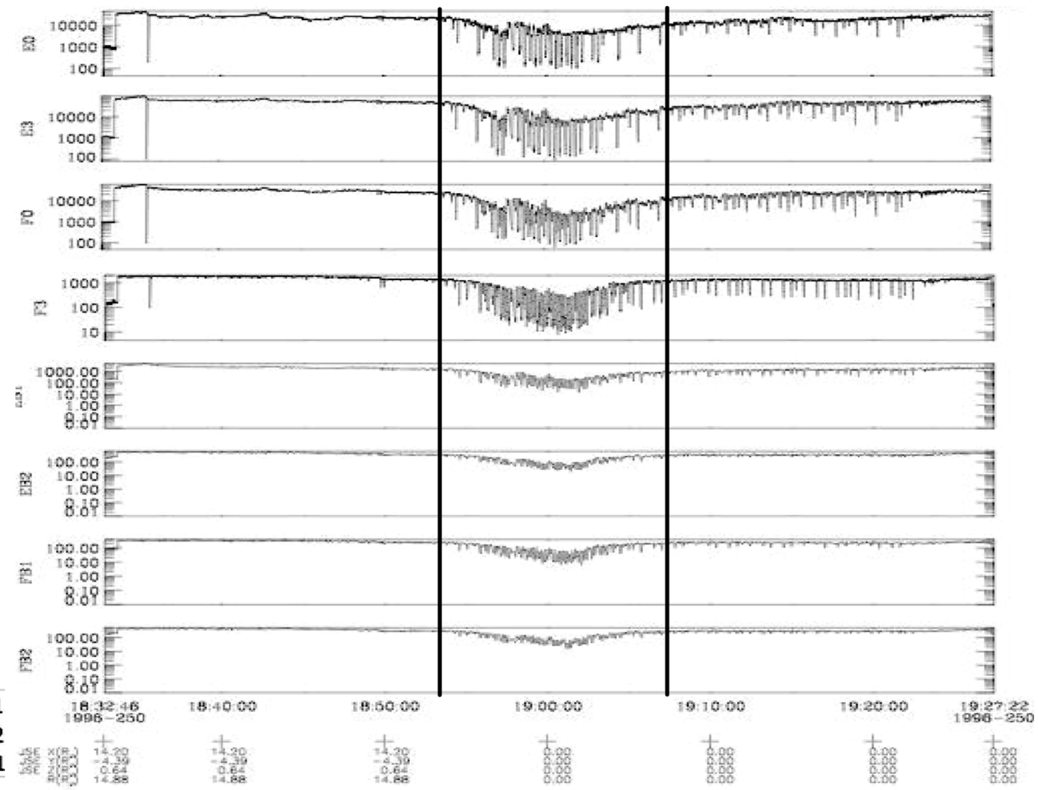
Flux Reductions at Ganymede

Galileo observed reductions in the particle fluxes as at Europa

Ganymede Flybys:	
G1	838.0 km (EPD off)
G2	*264.4 km*
G7	3104.9 km
G8	1606.2 km
G28	808.7 km

G2 High F1, F2, B1 Electron Fluxes

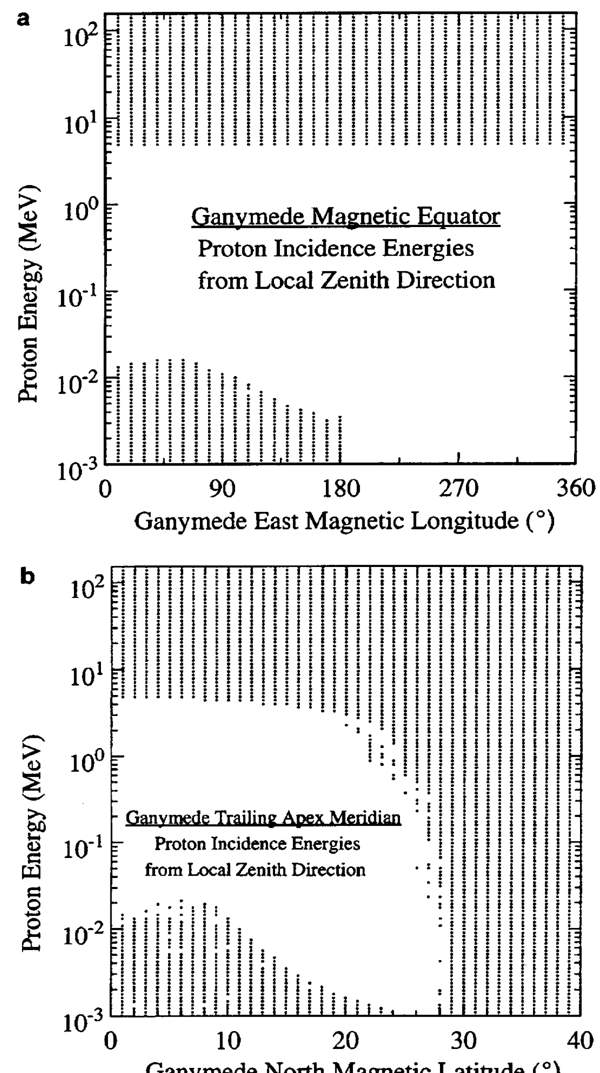




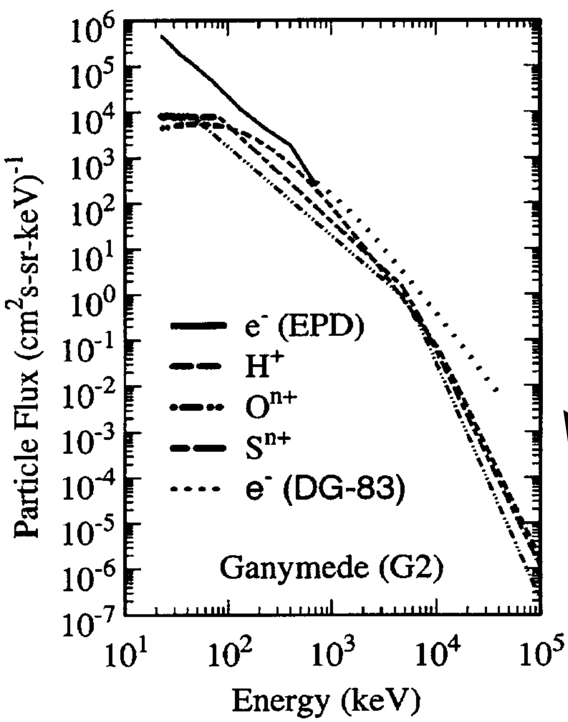
G2 Ganymede encounter EPD low-energy channel counts

Radiation Environment at Ganymede

Magnetic (a) east longitude and (b) north latitude for allowed trajectories incident from zenith onto Ganymede's surface. From Cooper et al. (2001)



From Cooper et al. (2001)



Flux spectra represent energetic particle environment upstream of Ganymede from EPD measurements during G2 encounter compared with Divine-Garrett (1983). From Cooper et al. (2001).

Radiation Modeling

Issues:

- Continued updates to Galileo-based electron/proton models will further the understanding of the jovian radiation environment
- Understanding the time-dependent, statistical variations of the jovian radiation belts provides better insight into the risk posture (effects of “storms”…)
- Heavy ion SEU rates at Jupiter will impact design choices (lessons learned from Galileo!)
- Improved models of the local Ganymede and Europa environments can take advantage of the “shielding” effects of the moons.

Radiation Modeling (Cont.)

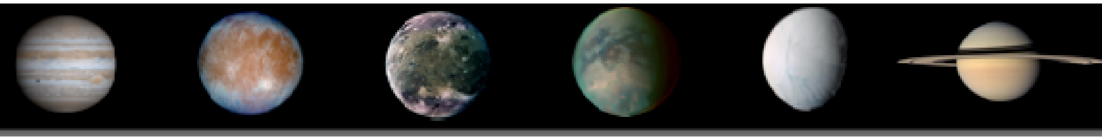
Steps to Reconcile Radiation Modeling Issues:

- Incorporate Galileo-based electron pitch angle model--leading to complete electron model update (GIRE II)
- Develop a Galileo-based proton model
- Complete Galileo-based, high energy heavy ion model (HIC)
- Model local Ganymede (and Europa*) magnetosphere radiation environment--Størmer Theory
- Model “storm” events observed by Galileo EPD

See Paranicas et al., 2007

Conclusions

- ***The original Divine radiation model (circa 1983) provided a good basis for spacecraft radiation design (e.g., Galileo's successful performance)***
- ***The 35 Galileo orbits provided excellent in-situ measurements of the jovian equatorial radiation environment and allowed significant updates to the Divine model:***
  - The GIRE model updated the 8-16 L high energy electron environment
  - Synchrotron modeling allowed updating the inner electron radiation environment
  - Statistical models have been developed to allow better risk modeling
  - Modeling of the local lunar radiation environments is underway
- ***We now have a "validated" heavy ion model (HIC)!***



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